Sound Speed and Attenuation in Multiphase Media

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LONG-TERM GOALS

One research goal developed from conducted shallow water (SW) acoustic transmission experiments in sandy-silty areas [1] revealed a nonlinear power law frequency-dependent attenuation at lower frequencies (≤ 1 kHz) consistent with results reviewed in [2-4] and the observations by the ONR-HEP program. The Biot Theory [5] predicts that the sandy- sediment frequency-dependent attenuation should be quadratic, $\alpha(f) = \alpha(f_o)(f / f_o)^n$ with $n = 2$; however the observed dependence was $n = 1.8 \pm 0.2$. Thus the long-range goal was to develop a simplified theory of sediment attenuation [6] verified by measurements that could explain this dependence and be applied to ocean sediments.

The second research goal is the development of a quantitative understanding and a theoretical treatment of the scattering of sound by non spherical compressible objects such as bubbles.

OBJECTIVE

The objective of the work, discussed in this annual report, was to determine the frequency dependent attenuation and phase speed characteristics of selected sandy and muddy sediments (both water saturated and partially saturated) at the lower frequencies to verify a simplified Biot theory] and to provide a theoretical / experimental basis for the water-sediment boundary condition necessary for the accurate prediction of wide band transmission loss in shallow waters.

APPROACH

This work was aimed at enhancing our understanding of saturated and partially saturated sandy sediment for frequencies ranging from 100 Hz to 10 kHz. The basic hypothesis is based on the simplified Biot sediment theory [6] and the prediction that high permeability sands will have a quadratic frequency dependent attenuation, and that these measure-ments can be described by a Biot time constant. Previously, the Nantucket Sound Experiment, have been [7, 8] we compared this theory to experimental results from an experiment with known environmental (isospeed) conditions, geophysical properties, surface roughness and water depth. While the theory predicts a power-law

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14. ABSTRACT

One research goal developed from conducted shallow water (SW) acoustic transmission experiments in sandy-silty areas [1] revealed a nonlinear power law frequency-dependent attenuation at lower frequencies (≤ 1 kHz) consistent with results reviewed in [2-4] and the observations by the ONR-HEP program. The Biot Theory [5] predicts that the sandy- sediment frequency-dependent attenuation should be quadratic, withnoo)f/f)(f()f(αα=2=n; however the observed dependence was . Thus the long-range goal was to develop a simplified theory of sediment attenuation [6] verified by measurements that could explain this dependence and be applied to ocean sediments

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dependence with an exponent of $n = 2$; results from this experiment agreed with other experiments conducted under similar conditions yielded an exponent on average of approximately

$$\alpha(f) = \alpha(f_o)\cdot(f/f_o)^n;\ \ with\ \ 0.261 \le \alpha(1\,kHz) \le 0.273\ and\ n = 1.87^{+0.17}_{-0.21}.$$

This compares with a summary by Zhou [2] drawn from a larger and less restrictive group of experimental results yielded $\alpha(f_o) = 0.34; n = 1.84$ where the reference frequency is not specified. The attenuation constant $\alpha(f_o)$ is consistent with the measurements of Hamilton [9] at 1 kHz.

For long-range propagation when shear is not important, as is the case for sandy silty sediments, the modal representation of the pressure field is

$$p(r) \approx \sum_{n=1}^{M} a_n \phi_n(z)\phi_n(z_o)H_o^1[(k_n + i\beta_n)r],$$

where ϕ_n, k_n, and β_n are the eigenfunction, the eigenvalue (or modal wavenumber), and modal attenuation coefficient of the n^{th} propagating mode. A perturbation solution for the modal coefficients that was originally developed by Kornhauser and Raney [10] and revisited by Pierce yields the modal attenuation coefficient as

$$\beta_n(\omega) = v_{ph,n}\{\int(\alpha(\omega)/\rho c)\phi_n^2 dz / \int(\phi_n^2/\rho)dz\}.$$

This expression shows that the modal attenuation is related to the intrinsic attenuation of the bottom by an integral over depth. Depth dependent profiles should be important in correctly determining the frequency dependence of attenuation. A comparison of the measured pressure field using the autonomous-vehicle hydrophone-array system with the pressure field calculated using a normal mode propagation code, such as Kraken [11], or with a poroelastic-parabolic-equation code, Ram, [12,13] with a depth dependent profiles and frequency dependent attenuation should explain this less than quadratic dependence.

Calculation with realistic near water sediment gradients in porosity, sound speed and attenuation were found to be inconsistent with these experimental results between 100 Hz and 1 kHz. The conclusion was that geoacoustic gradients could not explain the effect and since the surface roughness was negligent ($\sigma \approx 0.01m$) the leakage of sound from the channel by shear and interface waves were considered. The problem immediately faced is our lack of knowledge of the shear speed in the sandy-silty sediments. A review of experimental measurements revealed that the shear wave speed for sandy sediments with porosities in the 40-60% range should be less than 500 m/s.

Calculations with parabolic equation and fast field codes were performed to produce simulated pressure versus range data that when analyzed in the same manner as the experiments showed that low sediment shear wave speed could be important. The results of a calculation performed with a fluid bottom with $n = 2$ and $n = 1.8$ are shown in Fig. 1. The difference in the effective attenuation constant is seen to be largest at the lower frequencies. The $n = 2$ (the blue curve) results in an underestimate of this factor while the $n = 1.8$ result shows more attenuation at the lower frequencies. However when $n = 2$ is used with a shear wave speed of 300m/s the results are comparable with $n = 1.8$ result.

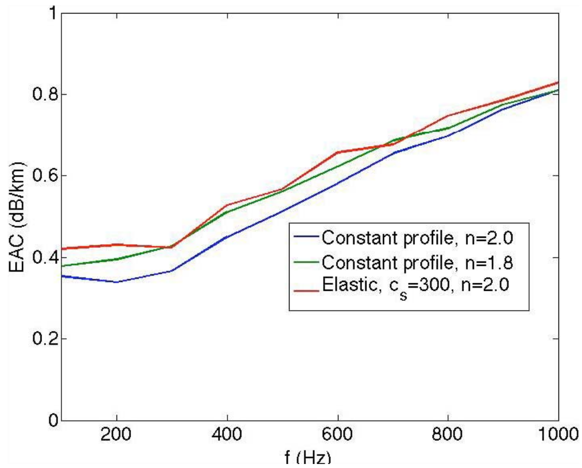

Fig. 1, A comparison of the calculated frequency dependence of the EAC for a liquid and poroelastic sediment with a shear speed of 300m/s.

The question posed by these result is the value of the shear wave speed in the Nantucket Sound Experiment and is it low enough to explain the $n = 1.8$ result?

WORK COMPLETED

The second Nantucket Sound Experiment used the autonomous-vehicle hydrophone-array system at a constant depth radially out from a source deployed on the water sediment interface from a small ship. Sensors on board the ship included a global positioning system, acoustic Doppler current profiler, a precision depth sounder, and a conductivity temperature-depth profiler. Source depth was determined by a depth sensor attached to the source and the source level was monitored with a reference hydrophone 1m from the source. A signal generator was used to generate signals composed of multiple narrow-band tones and the U.S. Navy calibrated source was driven with a Macintosh power amplifier.

The geometry for the experiment was a straight line tow past the source with the array just above the bottom. The six hydrophone outputs were recorded along with position information and vehicle speed. The results were narrow band filtered and range indexed. The complex pressure, $P(r,\omega)$, was then synthetically processed using a Hankle Transform to determine the horizontal wave number spectrum, $P(k,\omega) \cdot P(k,\omega)^{\bullet}$.

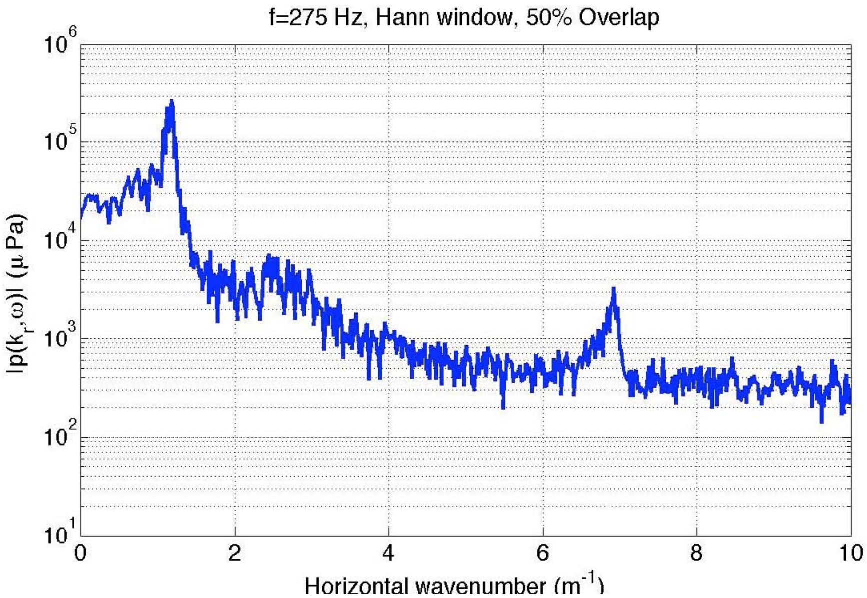

Fig. 2 The horizontal wave number spectrum at a frequency of 275 Hz , 0.38 s time sample, a Hann window on the Fourier Transfom and a 50% over lap. This result is from a linear average of horizontal wavenumber spectra from six hydrophones.

Figure 2 shows preliminary results from this experiment. The rlative amplitude peaks of the Sholte wave to Compressional wave is approximately 100. The Sholte wave peak at a wavenumber of 6.95 yields a shear wave spee of 284 m/s. This result is an unusual measurement of the sediment shear wave speed and is consistent with our expectation of the importance of waveguide energy removal by conversion to shear.

RESULTS

A rapid, accurate and cost effective waveguide characterization tool, a prototype autonomous-vehicle towed-hydrophone-array system, was used to perform two shallow water experiments. The attenuation result from the Nantucket Sound I experiment was found to have frequency dependence $n = 1.87$. Agreement between measured and calculated transmission loss was obtained when this non-linear frequency dependent attenuation with a magnitude consistent with Hamilton's results were used. However the difference between $n = 1.8$ *and* 2 could not be explained. Numerical calculations and experiments showed that the incorporation of shear yielded results consistent with the measured $n = 1.8$ value. That is leakage of energy into shear wave propagation could explain the measured nonlinear frequency dependence since the apparent attenuation of compression waves in the water would be determine by two effects, the intrinsic attenuation in the sediment and the conversion of compressional waves to shear waves.

An analytical treatment of a two layer waveguide, one layer being elastic sediment and the other water, showed that the modal attenuation, the removal of energy from the propagating modes, was composed of two terms-intrinsic attenuation and conversion to shear waves. This conversion at the lower frequencies was dependent on the shear wave speed to the third power, c_s^3, and that the interface, Sholte, wave would have a speed approximately $c_{sch} \approx 0.9\, c_s$. To determine c_s the Nantucket Sound II experiment was conducted with this same system , the source of sound on the bottom and the array towed just above the bottom. The measured horizontal-wave-number spectrum was found to have peaks due to compressional wave propagation in the water and an interface wave, Sholte Wave corresponding to a shear wave speed of $c_s \approx 280 m/s.$.

IMPACT/APPLICATIONS

The measurement system described above was capable of characterizing a 4 km course in less than 1 hour while previous techniques required up to 8 hours. Additionally, the experiments were performed from a single small ship with no moored assets. The autonomous-vehicle towed-array system is an accurate, cost-effective, and efficient ocean acoustics measurement and surveillance tool and will have an impact on ocean acoustic experiments. The additional attribute of shear speed measurement in the hundreds of Hertz range is significant.

RELATED PROJECTS

The results of this research have the potential for dramatically improving the use of geo-acoustic models to accurately predict the propagation and dispersion of sound at the low frequencies (~100 Hz) to the high frequencies (~10 kHz). This work initiated the post doctoral appointment of Jon Collis and is now closely coordinated with his current ONR post doctoral grant. This effort is related to ONR-OA investigations at the Woods Hole Oceanographic Institution and the Rensselaer Polytechnic Institute and results in sharing resources and students.

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HONORS

The Pioneers of Underwater Acoustics, Silver Medal of the Acoustical Society of America was awarded in June 2007 and will be received in November 2007